Searching for Extra Dimensions at the Tevatron

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(For the CDF & DØ Collaborations)

SSI '04

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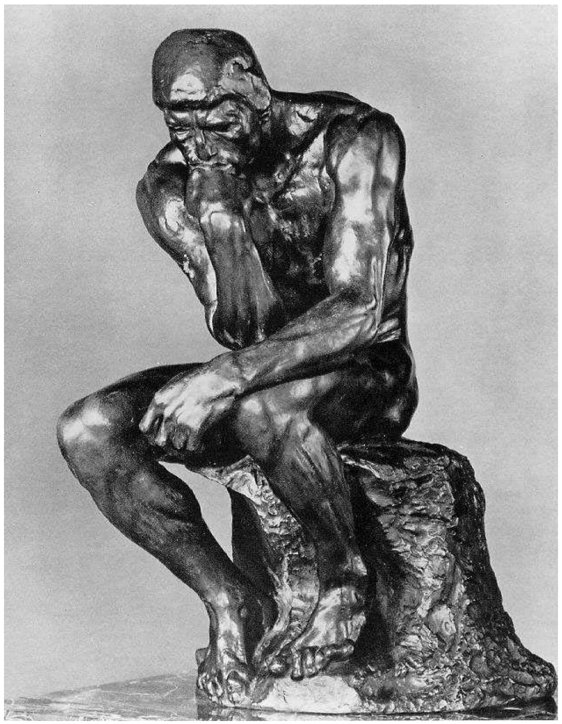
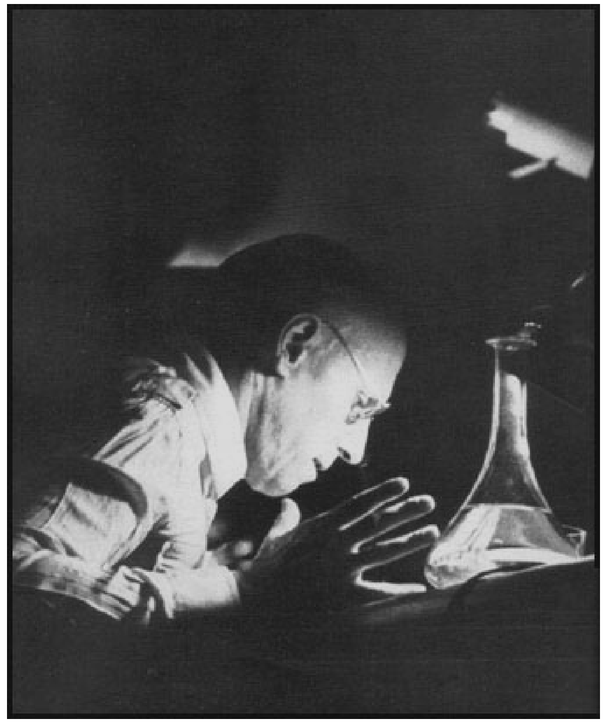
Out-Sketch

Theory/Phenomenology



See Tom Rizzo's Talk:
- ❖ Models
- ❖ Cosmology Constraints
- ❖ Future

Tabletop Experiments



See Sylvia Smullin's Talk:
- ❖ Gravity at short distances

Accelerator Searches

This Talk:
- ❖ Brief Theory Recap
- ❖ Tevatron & Detectors
- ❖ Searches:
  - o ADD Model
  - o TeV^{-1} Scenario
  - o RS Model
  - o Universal ED
  - o Use-Them-n-Lose-Them ED (little Higgs models)
- ❖ Conclusions

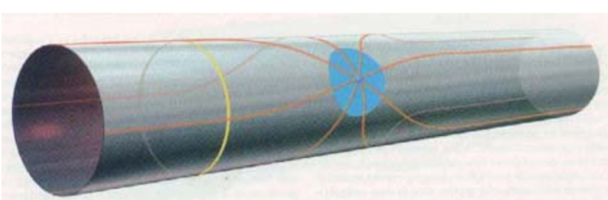
Big Why? (Or Math Meets Physics)

- Math physics: some dimensionalities are quite special
- Example: Laplace equation in two dimensions has logarithmic solution; for any higher number of dimensions it obeys power law instead
- Some of these peculiarities exhibit themselves in condensed matter physics, e.g. diffusion equation solutions allow for long-range correlations in 2D-systems (cf. flocking)
- Modern view in topology: one dimension is trivial; two and three spatial dimensions are special (properties are defined by the topology); any higher number is not
- Do we *live* in a special space, or only *believe* that we are special?

Difference Between the Models

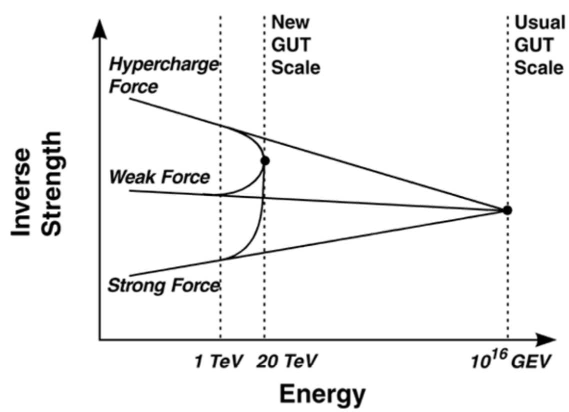
ADD Model:

- "Eliminates" the hierarchy problem by stating that physics ends at a TeV scale
- Only gravity lives in the "bulk" space
- Size of ED's (n=2-7) between ~100 μm and ~1 fm
- Doesn't explain how to make ED large



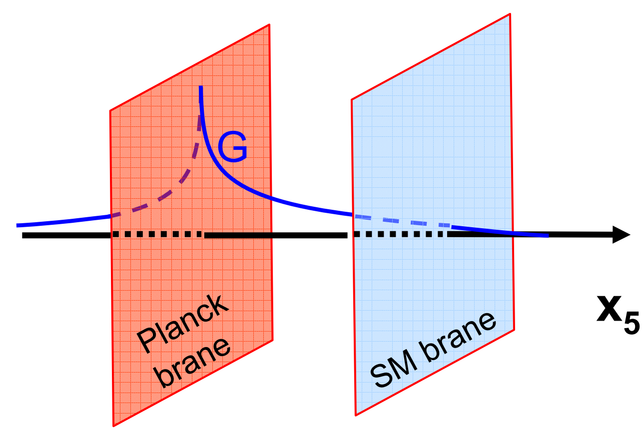
TeV-1 Scenario:

- Lowers GUT scale by changing the running of the couplings
- Only gauge bosons ($g/\gamma/W/Z$) propagate in a single ED; gravity is not in the picture
- Size of the ED ~1 TeV^{-1} or ~10^{-19} m



RS Model:

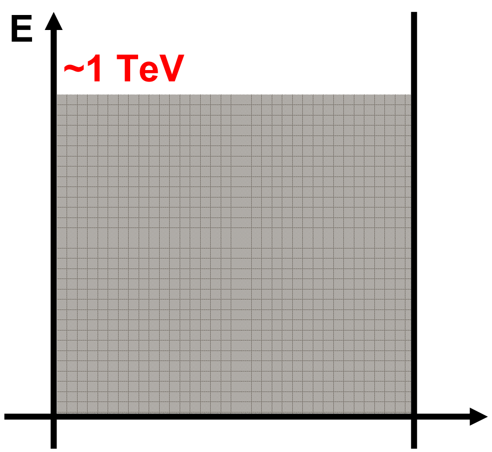
- A rigorous solution to the hierarchy problem via localization of gravity
- Gravitons (and possibly other particles) propagate in a single ED, w/ special metric
- Size of this ED as small as ~$1/M_{Pl}$ or ~10^{-35} m



Kaluza-Klein Spectrum

ADD Model:

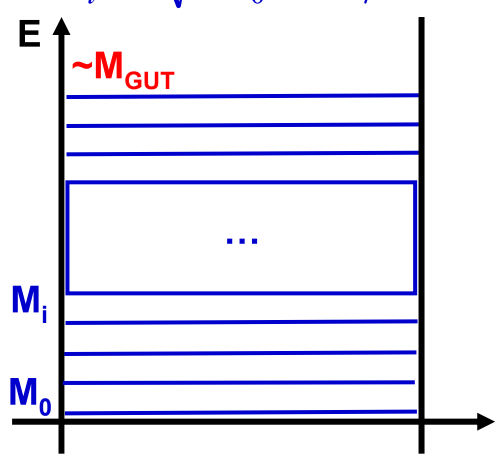
- Winding modes with energy spacing ~1/r, i.e. 1 meV – 100 MeV
- Can't resolve these modes – they appear as continuous spectrum



TeV^{-1} Scenario:

- Winding modes with nearly equal energy spacing ~1/r, i.e. ~TeV
- Can excite individual modes at colliders or look for indirect effects

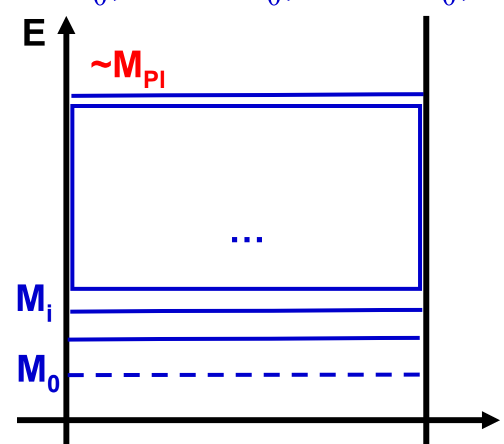
$$M_i = \sqrt{M_0^2 + i^2/r^2}$$



RS Model:

- "Particle in a box" with a special metric
- Energy eigenvalues are given by zeroes of Bessel function J_1
- Light modes might be accessible at colliders

$$M_i = M_0\, x_i/x_0 \approx M_0, 1.83M_0, 2.66M_0, 3.48M_0, 4.30M_0, \ldots$$

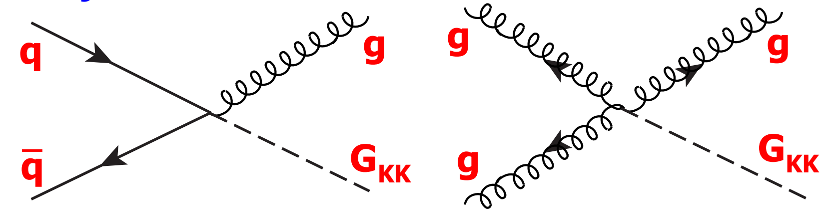


Collider Signatures for Large Extra Dimensions

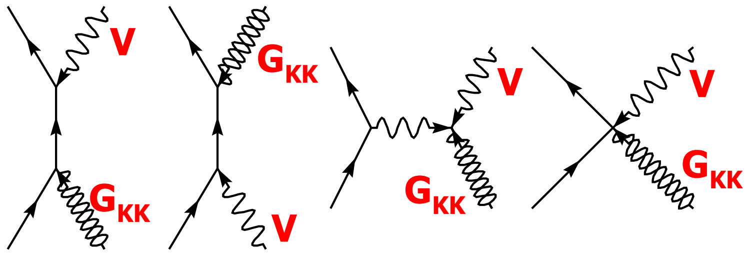
- Kaluza-Klein gravitons couple to the energy-momentum tensor, and therefore contribute to most of the SM processes
- For Feynman rules for G_{KK} see:
  - Han, Lykken, Zhang, PR **D59**, 105006 (1999)
  - Giudice, Rattazzi, Wells, Nucl. Phys. **B544**, 3 (1999)
- Since graviton can propagate in the bulk, energy and momentum are not conserved in the G_{KK} emission from the point of view of our 3+1 space-time
- Depending on whether the G_{KK} leaves our world or remains virtual, the collider signatures include single photons/Z/jets with missing E_T or fermion/vector boson pair production
- Graviton emission: direct sensitivity to the fundamental Planck scale M_D
- Virtual effects: sensitive to the ultraviolet cutoff M_S, expected to be $\sim M_D$ (and likely $< M_D$)
- The two processes are complementary

Real Graviton Emission

Monojets at hadron colliders

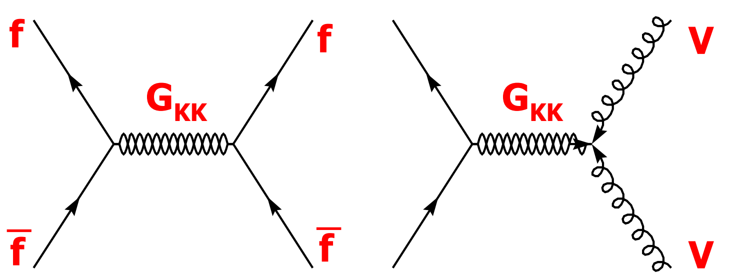


Single VB at hadron or e^+e^- colliders

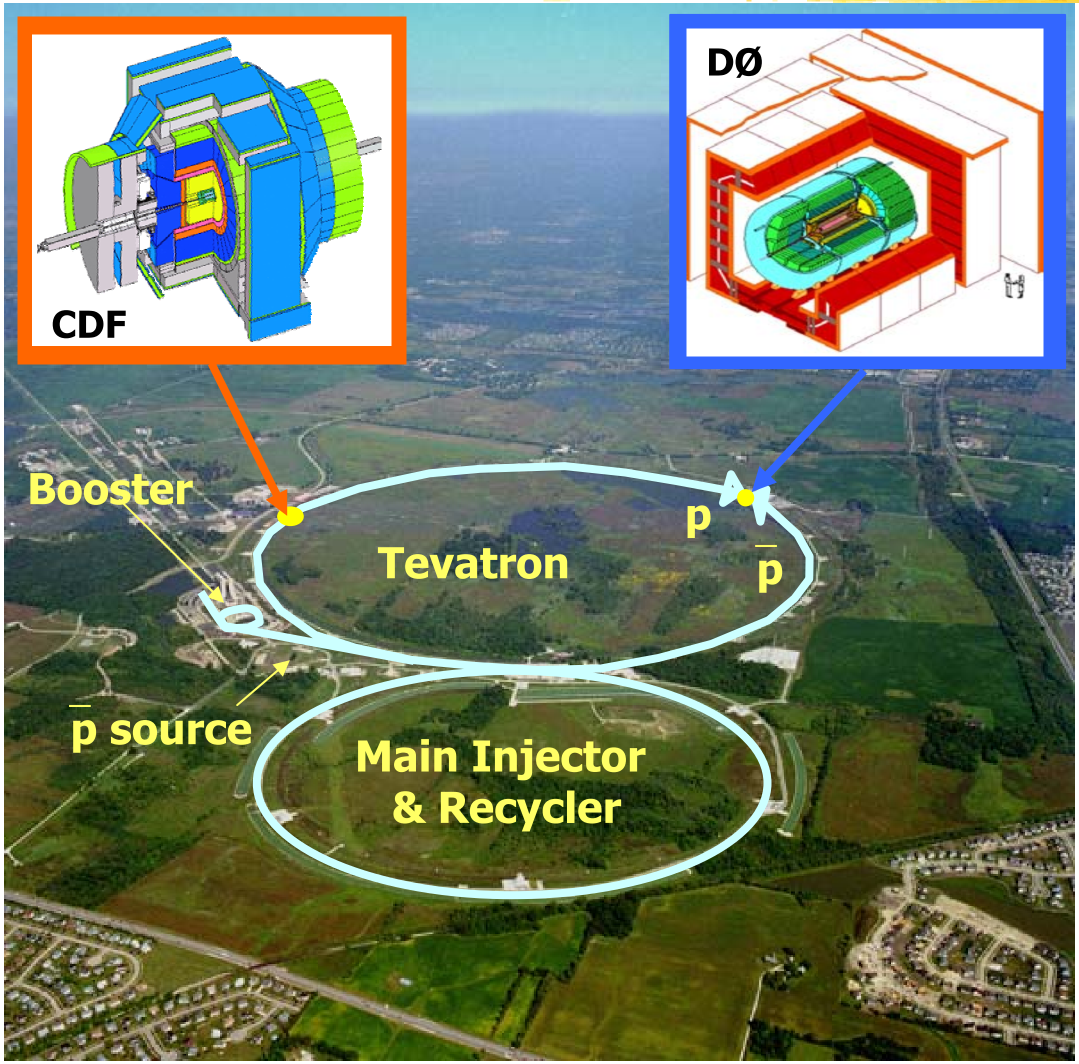


Virtual Graviton Emission

Fermion or VB pairs at hadron or e^+e^- colliders



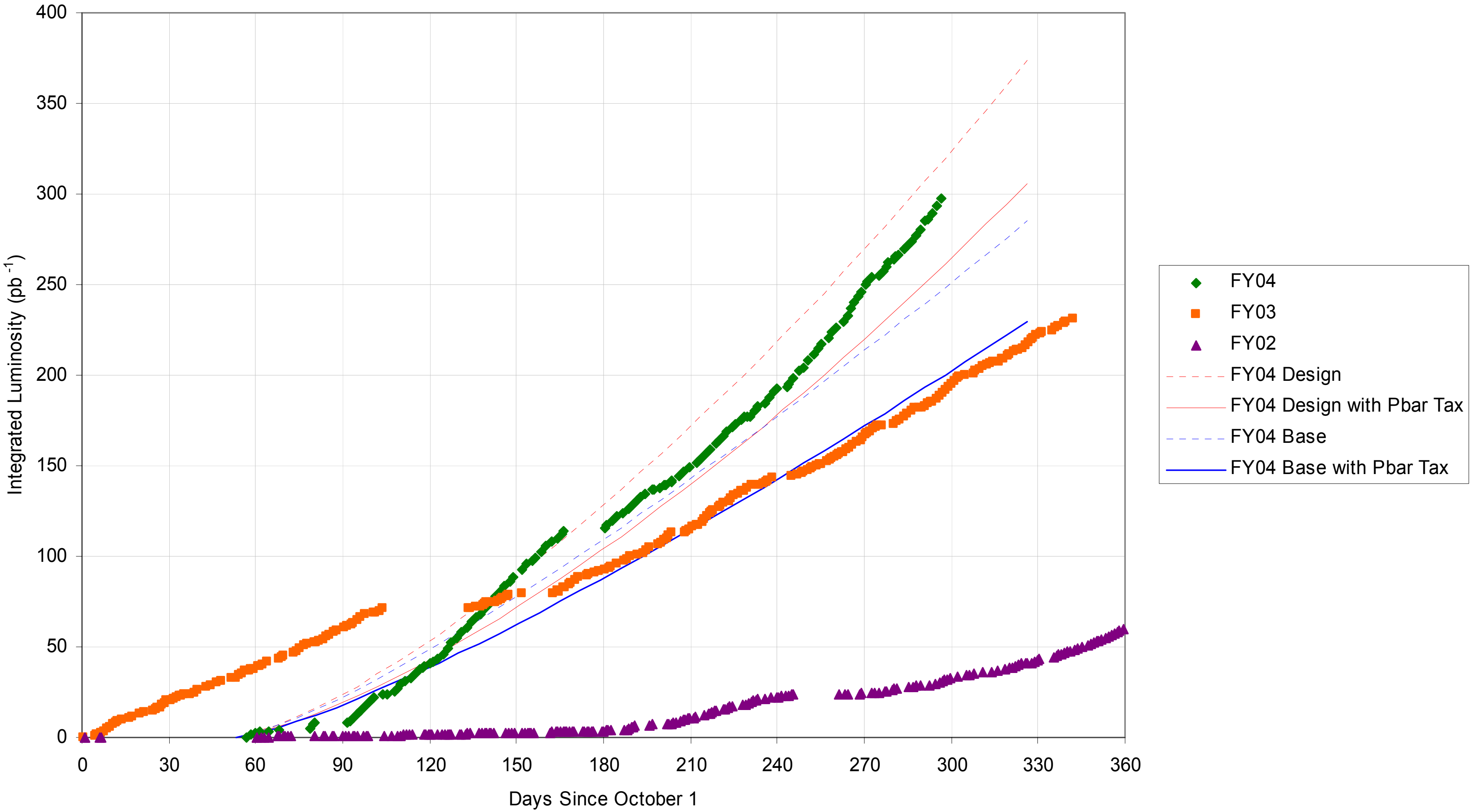
Run II Vital Statistics



- Significant upgrade of the detectors and the accelerator complex:
  - New main injector and antiproton recycler
  - Higher c.o.m. energy: (1.8 TeV → 1.96 TeV)
  - Shorter bunch crossing: (3.5 μs → 396 ns)
  - More proton and antiproton bunches: (6 x 6 → 36 x 36)
  - Projected integrated luminosity per experiment:
    - ~2 fb^{-1} (2006)
    - ~8 fb^{-1} (2009)
- Slow start but we caught up!
- Highest luminosity so far: 1.03 x 10^{32} $cm^{-2}s^{-1}$
- Nearly 0.5 fb^{-1} of data on tape per experiment to date
- Data taking efficiency: 85-90%

Tevatron Performance

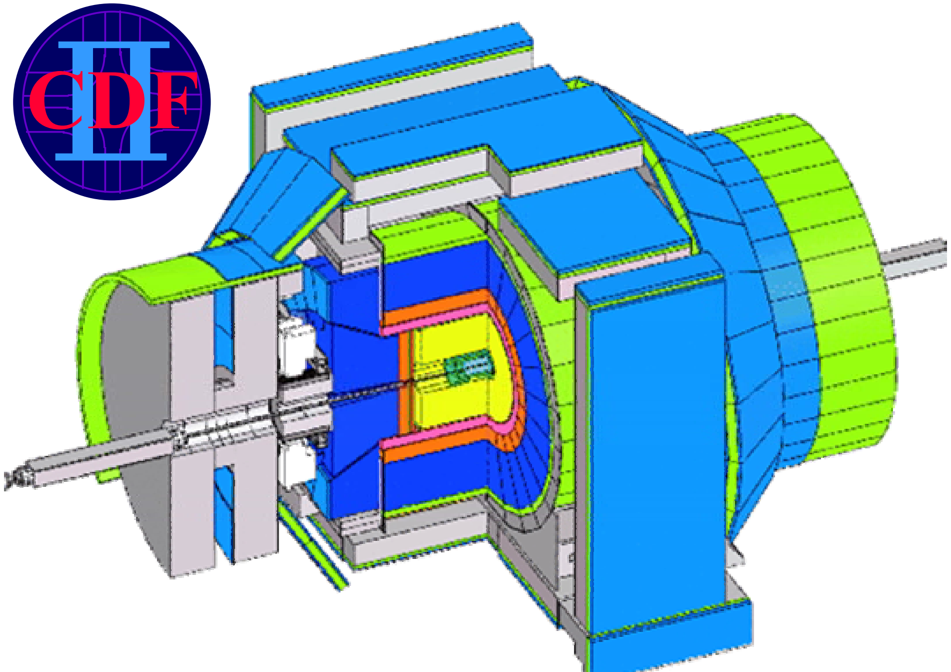
The FY2004 Design goal (306 pb^{-1} delivered) has been achieved last week

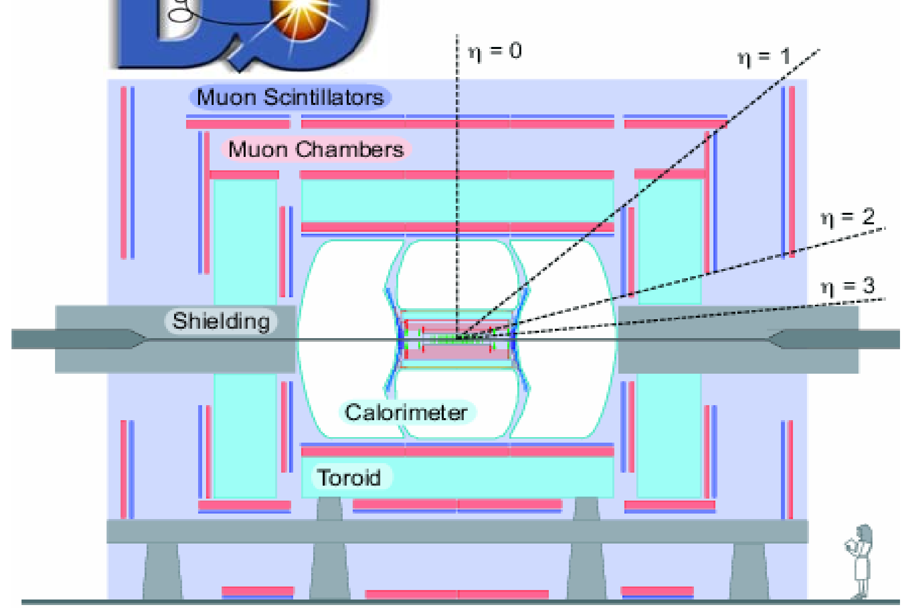


CDF and DØ

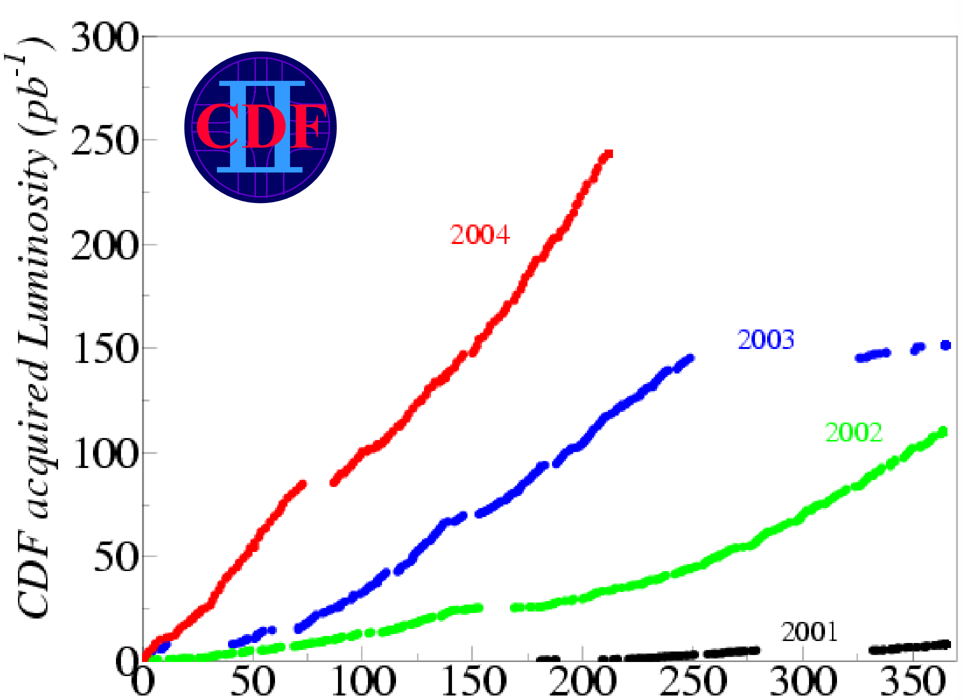
- New:
  - ❖ silicon detector, drift chamber
  - ❖ TOF PID system
- Upgraded:
  - ❖ calorimeter, muon system
  - ❖ DAQ/trigger, displaced-vertex trigger

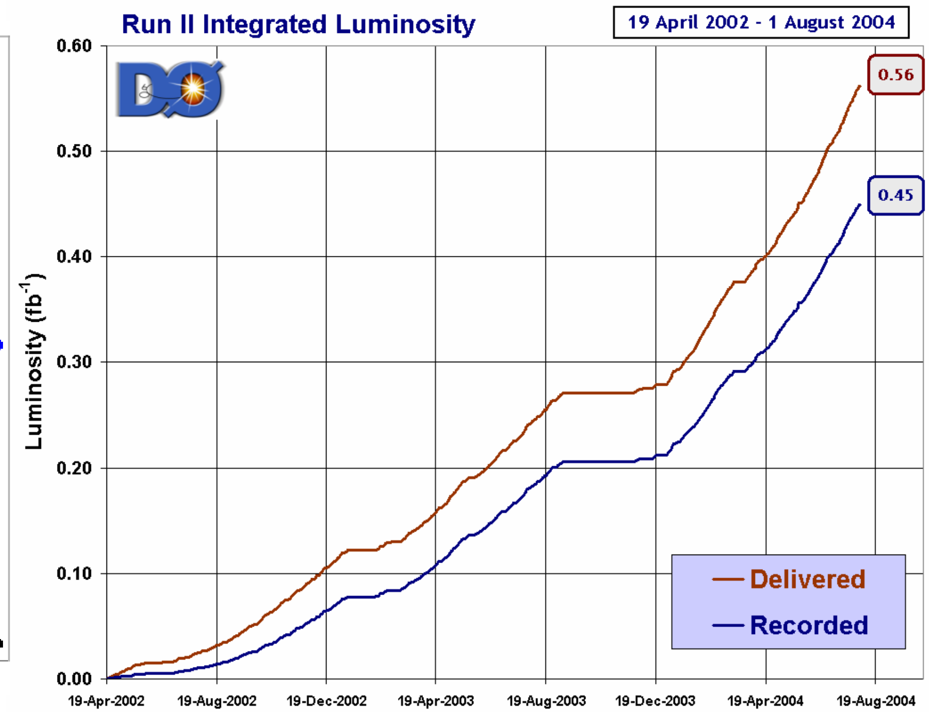
- New:
  - ❖ 2T superconducting solenoid
  - ❖ silicon detector, fiber tracker
- Upgraded:
  - ❖ FE electronics, muon system
  - ❖ DAQ/trigger, displaced-vertex trigger





CDF & DØ Performance



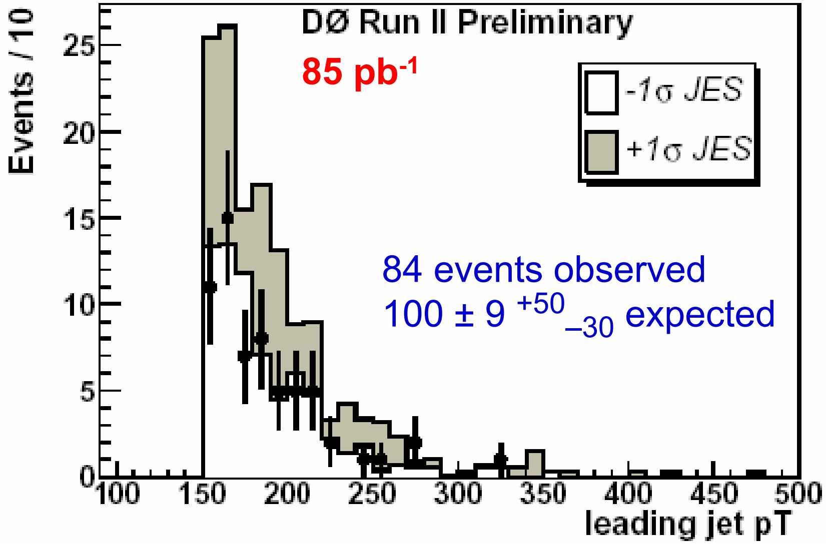


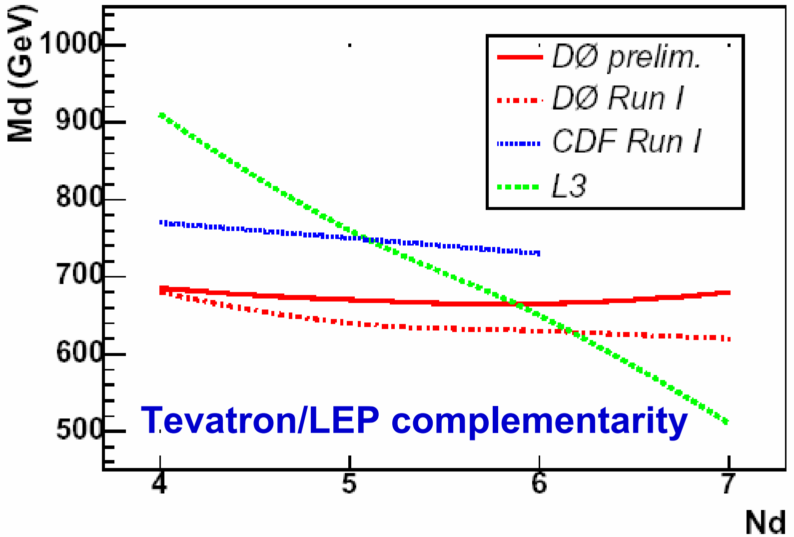
1 billion events recorded as of August 2!

- Both experiments are ≈85% efficient over the last year
- Most of the analyses shown in this talk are based on ~200 pb^{-1}, which corresponds to 2002-2003 data

Search for Monojets

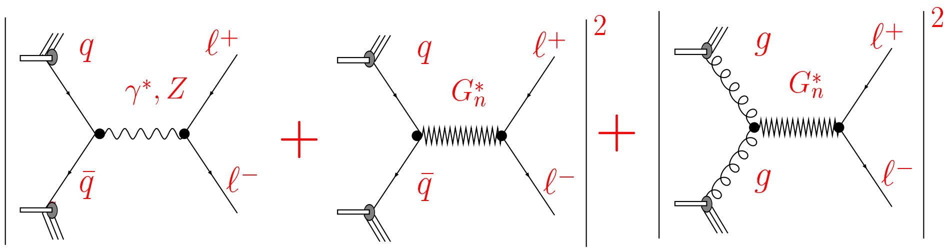
- Challenge: large instrumental background from ME_T mismeasurement and cosmics
- Irreducible physics background from $Z(\nu\nu)$ + jet(s): forced to use high jet P_T, ME_T cuts
- Pioneered in Run I by DØ [PRL **90**, 251802 (2003)]: $M_D > 0.63 - 0.89$ TeV (n=6-2)
- Recently superseded by CDF [PRL **92**, 121802 (2004)]: $M_D > 0.71 - 1.00$ TeV (n=6-2)
- CDF also pioneered similar search in $\gamma+ME_T$, albeit less sensitive [PRL **89**, 281801 (2002)]
- New Run II analysis from DØ based on 85 pb^{-1} of data collected with special trigger
  - Major systematics from jet energy scale – to be reduced soon
  - Sensitivity already exceeds that for DØ in Run I, but still below the CDF's Run I result
  - Impressive sensitivity already achieved with less data due to superior detector and higher energy





Virtual Graviton Effects

- In the case of pair production via virtual graviton, gravity effects interfere with the SM (e.g., l^+l^- at hadron colliders):



- Therefore, production cross section has three terms: SM, interference, and direct gravity effects:

$$\frac{d^2\sigma}{d\cos\theta^* dM} = \frac{d^2\sigma_{SM}}{d\cos\theta^* dM} + \frac{a(n)}{M_S^4} f_1\left(\cos\theta^*, M\right) + \frac{a(n)^2}{M_S^8} f_2\left(\cos\theta^*, M\right)$$

- The sum in KK states is divergent in the effective theory, so in order to calculate the cross sections, an explicit cut-off is required
- An expected value of the cut-off $M_S \approx M_D$, as this is the scale at which the effective theory breaks down, and the string theory needs to be used to calculate production
- There are three major conventions on how to write the effective Lagrangian:
  - Hewett, Phys. Rev. Lett. **82**, 4765 (1999)
  - Giudice, Rattazzi, Wells, Nucl. Phys. **B544**, 3 (1999); revised version, hep-ph/9811291
  - Han, Lykken, Zhang, Phys. Rev. **D59**, 105006 (1999); revised version, hep-ph/9811350
- Fortunately all three conventions turned out to be equivalent and only the definitions of M_S are different

Hewett, GRW, and HLZ Formalisms

- Hewett: neither sign of the interference nor the dependence on the number of extra dimensions is known; therefore the interference term is $\sim\lambda/M_S^4$(Hewett), where λ is of order 1; numerically uses $\lambda = \pm1$
- GRW: sign of the interference is fixed, but the dependence on the number of extra dimensions is unknown; therefore the interference term is $\sim 1/\Lambda_T^4$ (where Λ_T is their notation for M_S)
- HLZ: not only the sign of interference is fixed, but the n-dependence can be calculated in the effective theory; thus the interference term is $\sim\mathcal{F}/M_S^4$(HLZ), where $\mathcal{F}$ reflects the dependence on the number of extra dimensions:

$$\mathcal{F} = \begin{cases} \log\left(\frac{M_S^2}{s}\right), n = 2 \\ \frac{2}{n-2}, \; n > 2 \end{cases}$$

- Correspondence between the three formalisms:

$$M_S(\text{Hewett})\big|_{\lambda=+1} \equiv \sqrt[4]{\frac{2}{\pi}}\Lambda_T(\text{GRW})$$

$$\frac{\lambda}{M_S^4(\text{Hewett})} = \frac{\pi}{2}\frac{\mathcal{F}}{M_S^4(\text{HLZ})}$$

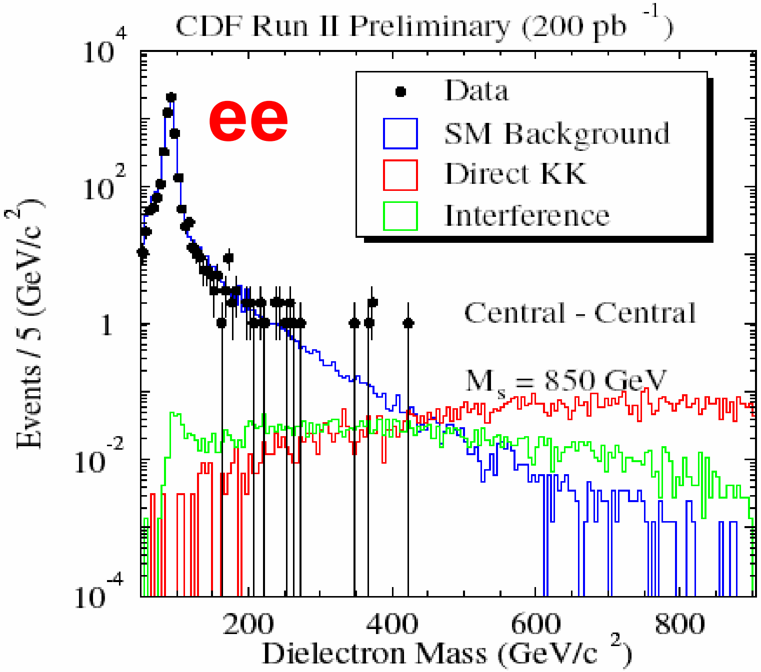
$$\frac{1}{\Lambda_T^4(\text{GRW})} = \frac{\mathcal{F}}{M_S^4(\text{HLZ})}$$

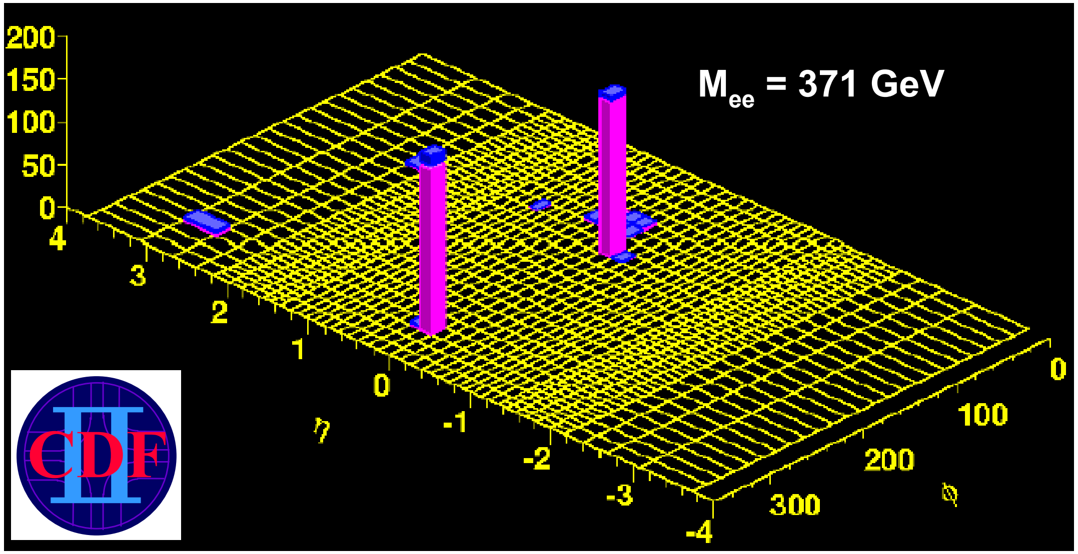
- Rule of thumb:

$$M_S(\text{Hewett})\big|_{\lambda=+1} \approx M_S(\text{HLZ})\big|_{n=5}$$

$$\Lambda_T(\text{GRW}) = M_S(\text{HLZ})\big|_{n=4}$$

CDF Search for Virtual Graviton Effects



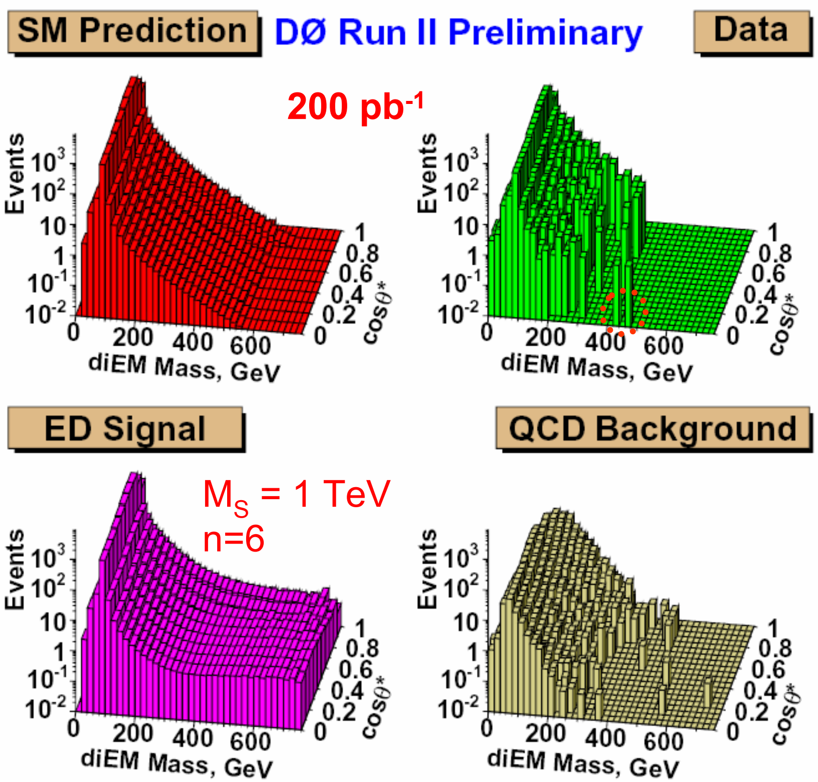


CDF Run II Preliminary (200 pb^{-1})

	η_{95} (10^{-12}GeV^{-4})		Hewett (GeV)		HLZ (GeV)					GRW (GeV)
	$\lambda < 0$	$\lambda > 0$	$\lambda < 0$	$\lambda > 0$	$n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$	
Central-Central	1.05	1.18	987	959	1315	1105	999	929	879	1105
Central-Plug	2.23	2.47	818	797	1089	916	827	770	728	916
Combined	1.05	1.18	987	959	1315	1105	999	929	879	1105

DØ Search for Virtual Graviton Effects

- Combine diphotons and dielectrons into "di-EM objects" to maximize efficiency
- High-mass, low $|\cos\theta^*|$ tail is a characteristic signature of LED [Cheung, GL, PRD **62** 076003 (2000)]



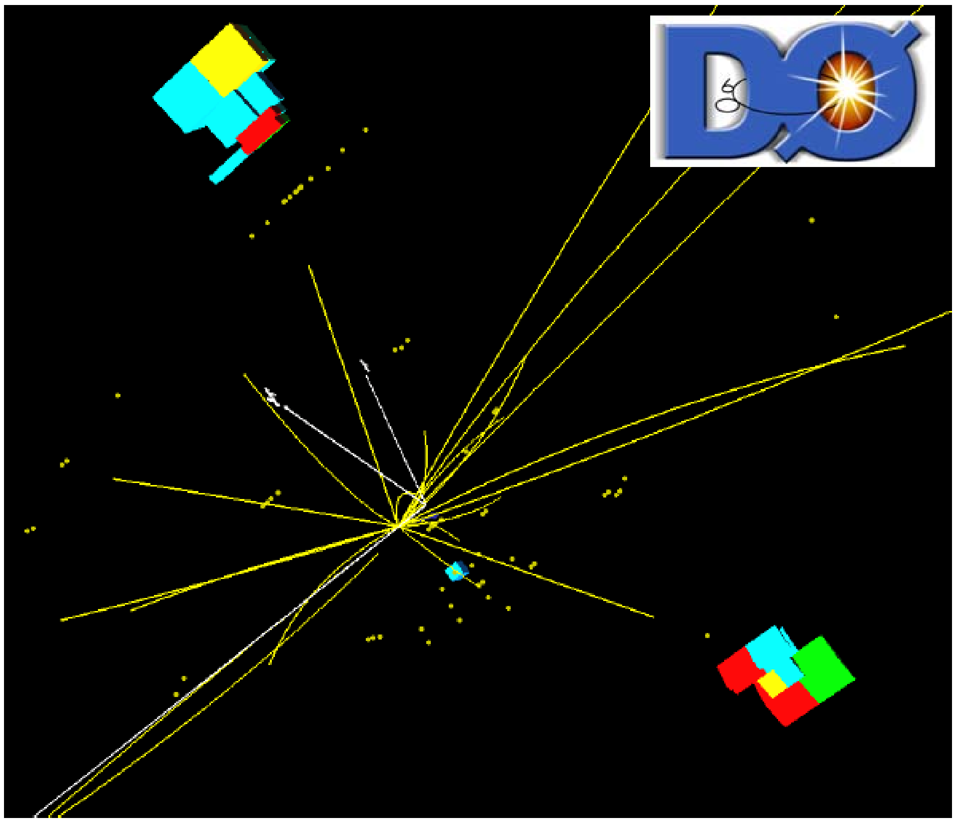
- Sensitivity is dominated by the diphoton channel ($2 \rightarrow 1 + 1$)
- Data agree well with the SM predictions; proceed with setting limits on large ED: alone or in combination with our Run I result [PRL **86**, 1156 (2001)]:

Hewett		GRW	HLZ					(TeV, @95% CL)
$\lambda = +1$	$\lambda = -1$		$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$	$n = 7$
1.22	1.10	1.36	1.56	1.61	1.36	1.23	1.14	1.08
1.28	1.16	1.43	1.67	1.70	1.43	1.29	1.20	1.14
		r_{max}	170 μm	1.5 nm	5.7 pm	0.2 pm	21 fm	4.2 fm

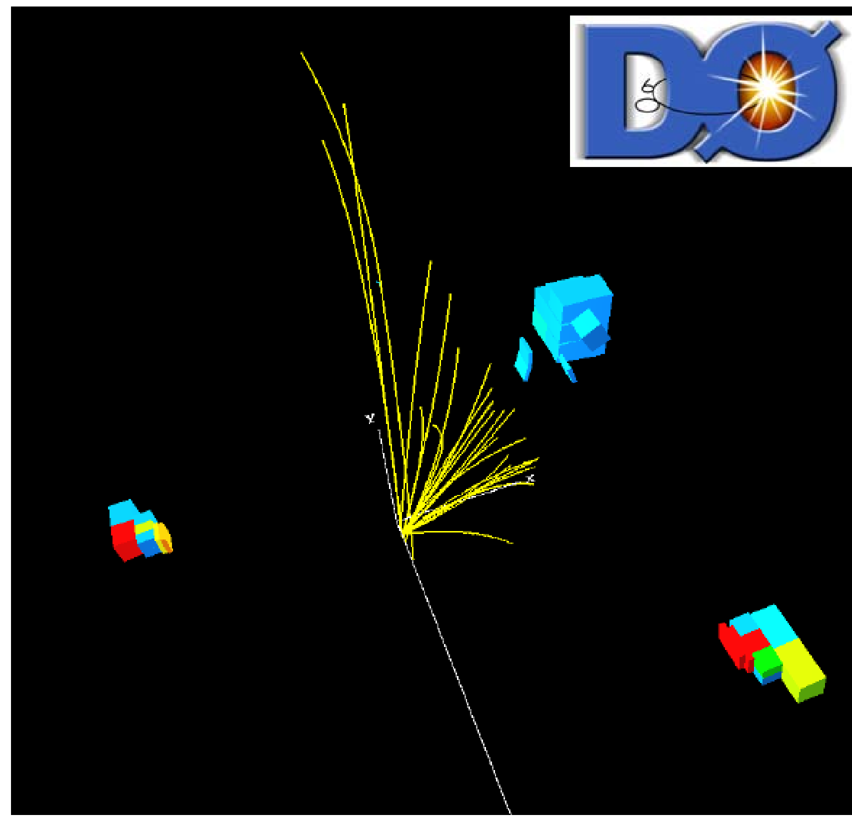
- These are the most stringent constraints on large ED for n > 2 to date, among all the experiments
- For n=2, the sensitivity is very close to that of the tabletop gravity measurements (M_D = 1.7 TeV, r < 160 μm)

Interesting Candidate Events

- While the DØ data are consistent with the SM, the two highest-mass candidates have anomalously low value of $\cos\theta^*$ typical of ED signal:



Event Callas: M_{ee} = 475 GeV, $\cos\eta^*$ = 0.01

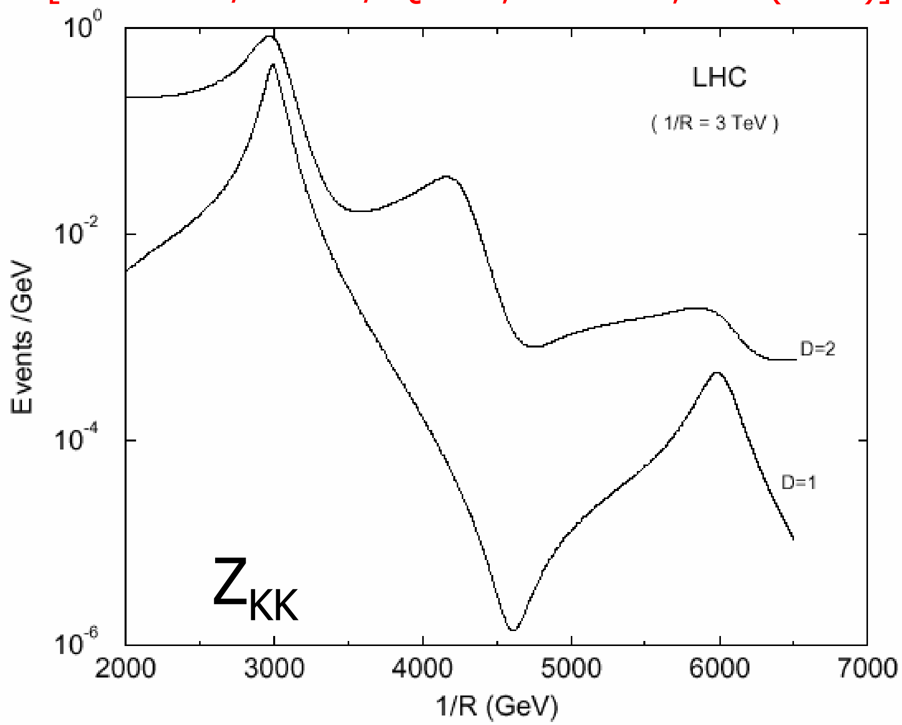


$M_{\gamma\gamma}$ = 436 GeV, $\cos\eta^*$ = 0.03

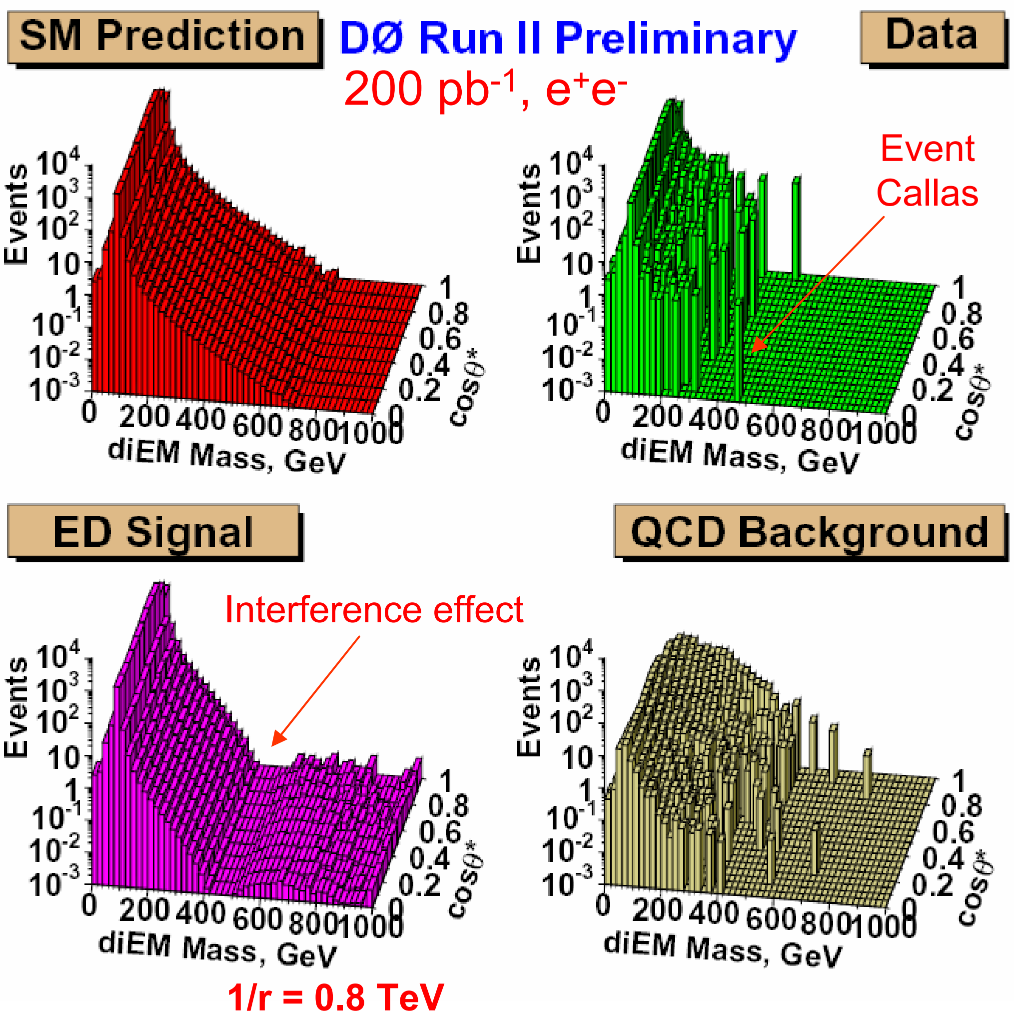
TeV^{-1} Extra Dimensions

- Intermediate-size extra dimensions with ~TeV^{-1} radius
- Introduced by Antoniadis [PL **B246**, 377 (1990)] in the string theory context; used by Dienes/Dudas/Gherghetta [PL **B436**, 55 (1998)] to allow for low-energy unification
  - Expect Z_{KK}, W_{KK}, g_{KK} resonances at the LHC energies
  - At lower energies, can study effects of virtual exchange of the Kaluza-Klein modes of vector bosons
- Current indirect constraints come from precision EW measurements: 1/r ~ 6 TeV
- No dedicated experimental searches at colliders to date

[Antoniadis/Benakli/sQuiros, PL **B460**, 176 (1999)]



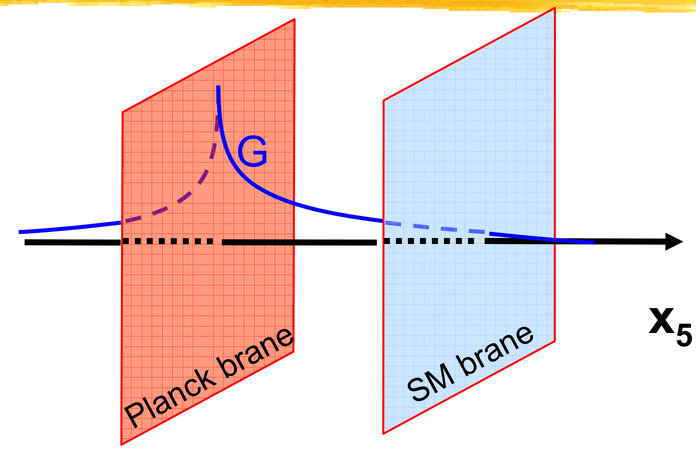
First Dedicated Search for TeV^{-1} Extra Dimensions

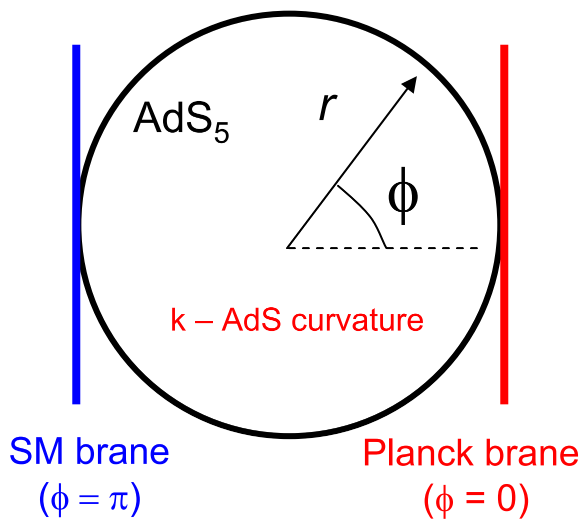


- While the Tevatron sensitivity is inferior to the indirect limit, it's searching for effects of virtual KK modes, as they are complementary to those in the EW data
- DØ has performed the first dedicated search of this kind in the dielectron channel based on 200 pb^{-1} of Run II data (Z_{KK}, $\gamma_{KK} \to e^+e^-$)
- The 2D-technique similar to the search for ADD effects in the virtual exchange yields the best sensitivity in the DY production [Cheung/GL, PRD **65**, 076003 (2002)]
- Data agree with the SM predictions, which resulted in the following limit on their size:
  - $1/r > 1.12$ TeV @ 95% CL
  - $r < 1.75 \times 10^{-19}$ m

Randall-Sundrum Scenario

- Randall-Sundrum (RS) scenario [PRL **83**, 3370 (1999); PRL **83**, 4690 (1999)]
  - \+ brane – no low energy effects
  - +– branes – TeV Kaluza-Klein modes of graviton
  - Low energy effects are given by Λ_π; for $kr_c \sim 10$, $\Lambda_\pi \sim 1$ TeV and the hierarchy problem is solved naturally
  - Zero-mode coupling is suppressed as $1/M_{Pl}$; other modes are coupled as $1/\Lambda_T$





$$ds^2 = e^{-2kr|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r^2 d\phi^2$$

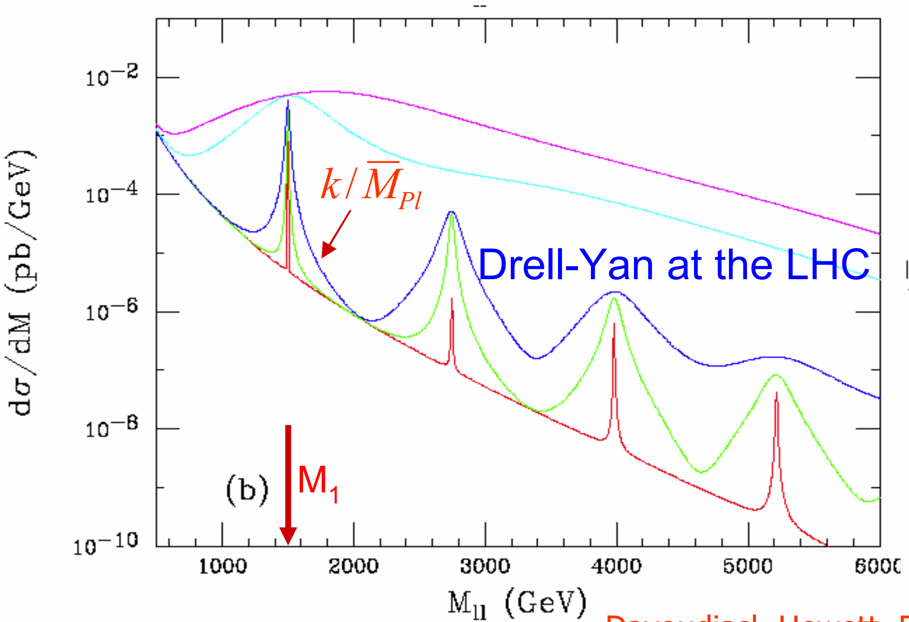
$$\Lambda_\pi = \overline{M}_{Pl}e^{-kr\pi}$$

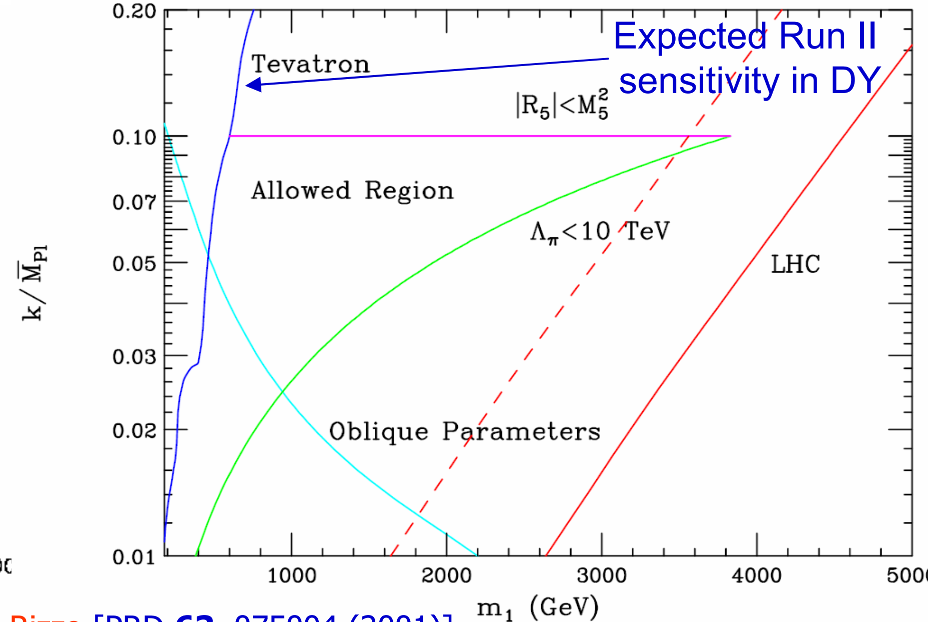
Reduced Planck mass:

$$\boxed{\overline{M}_{Pl} \equiv M_{Pl}/\sqrt{8\pi}}$$

Model Parameters

- Need only two parameters to define the model: k and r_c
- Equivalent set of parameters are:
  - The mass of the first KK mode, M_1
  - Dimensionless coupling $k/\overline{M}_{Pl}$
- To avoid fine-tuning and non-perturbative regime, coupling can't be too large or too small
- $0.01 \leq k/\overline{M}_{Pl} \leq 0.10$ is the expected range
- Gravitons are narrow

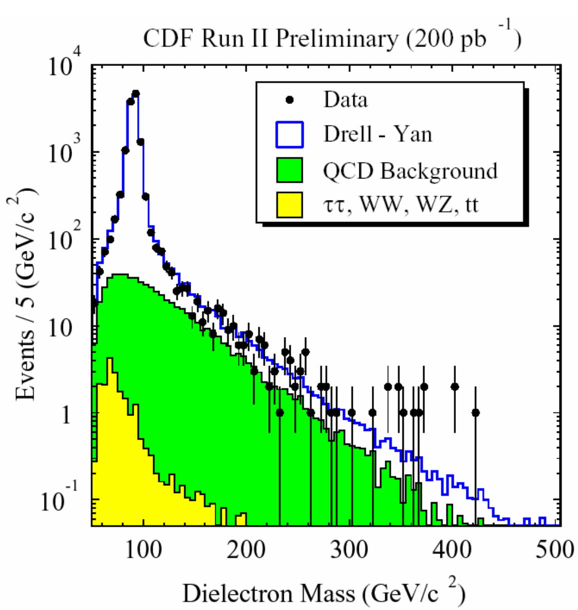


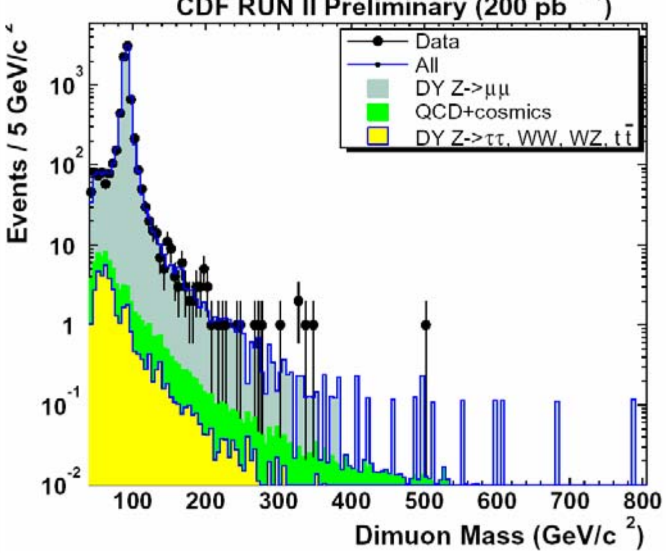


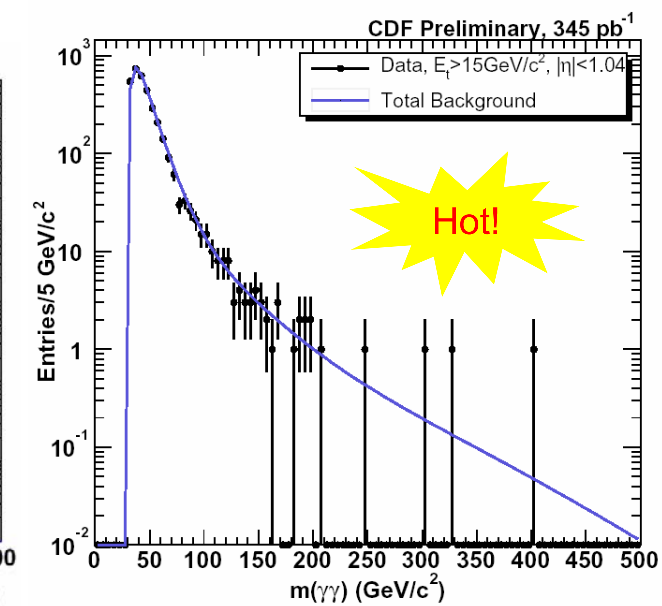
Davoudiasl, Hewett, Rizzo [PRD **63**, 075004 (2001)]

CDF Search for RS Gravitons

- CDF pioneered these search in 2003
- Based on e^+e^-, $\mu^+\mu^-$ (200 pb^{-1}) and $\gamma\gamma$ (345 pb^{-1}, central photons only) modes
- N.B.: $B(G \to gg) \approx 2B(G \to e^+e^-)$; diphotons also have higher acceptance
- Counting experiment in a resolution-driven sliding window in mass
- Data agree with expected SM background
- Interpret this as a search for narrow RS gravitons to set limits on the model parameters

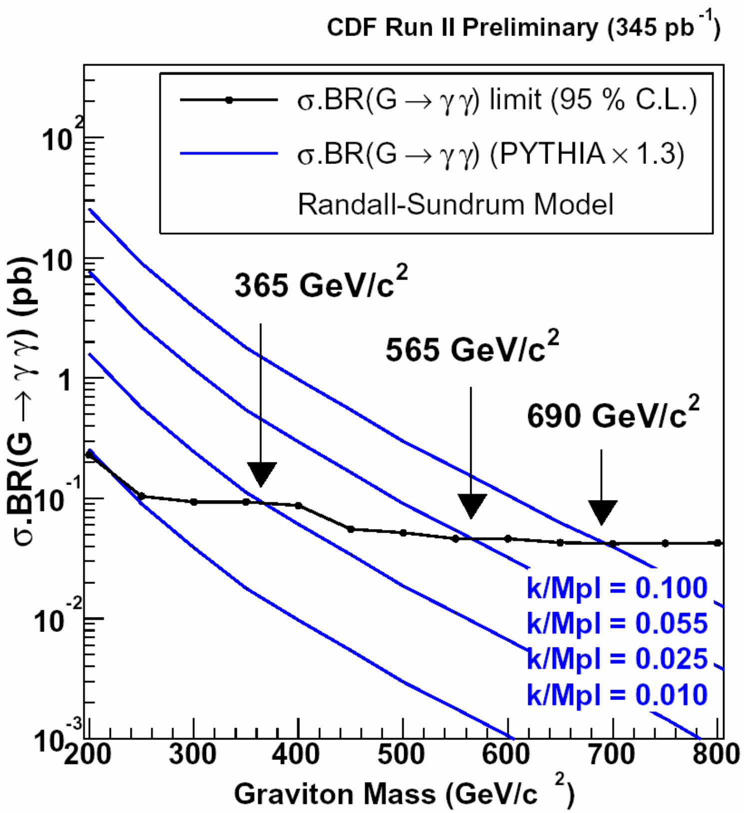


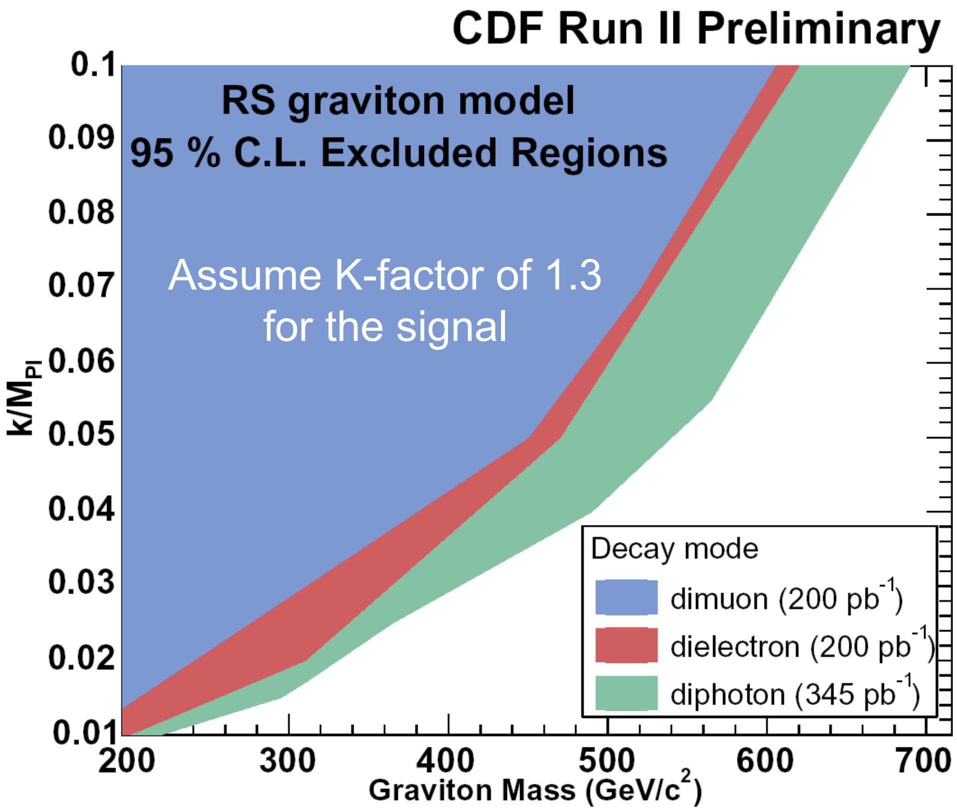




CDF Limits on RS Model

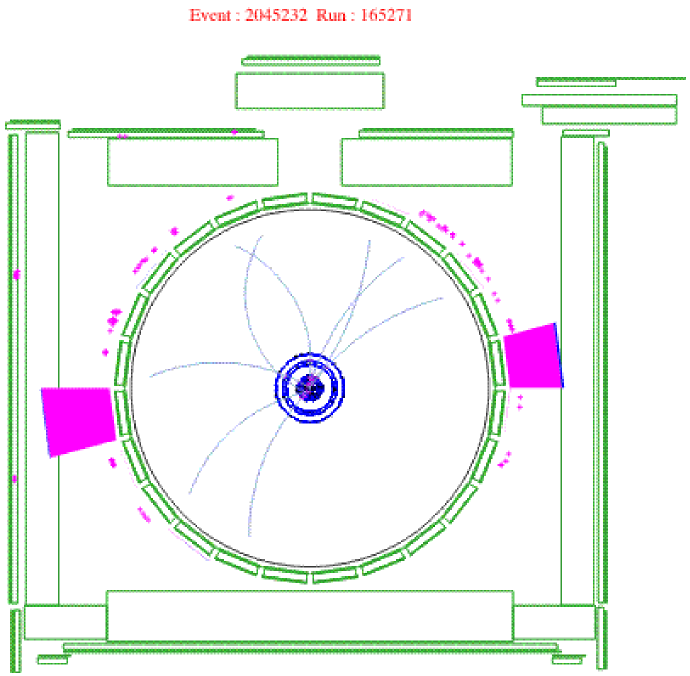
- Sensitivity is driven by the diphoton channel
- Gravitons with masses up to 690 GeV have been excluded for the coupling of 0.10
- Further improvement can be achieved by combining three channels (to be done!)





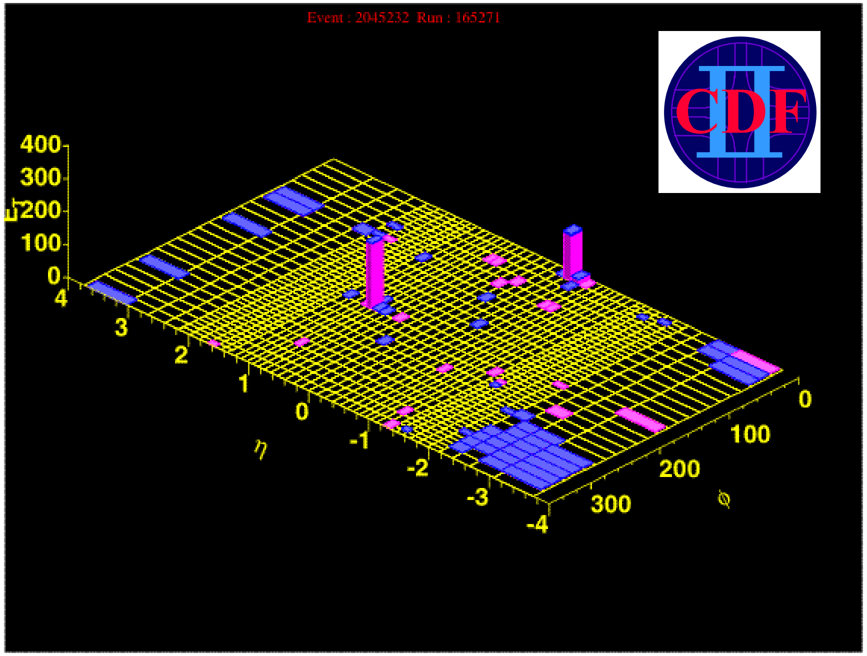
The Highest Mass Diphoton Event

$M_{\gamma\gamma}$ = 405 GeV



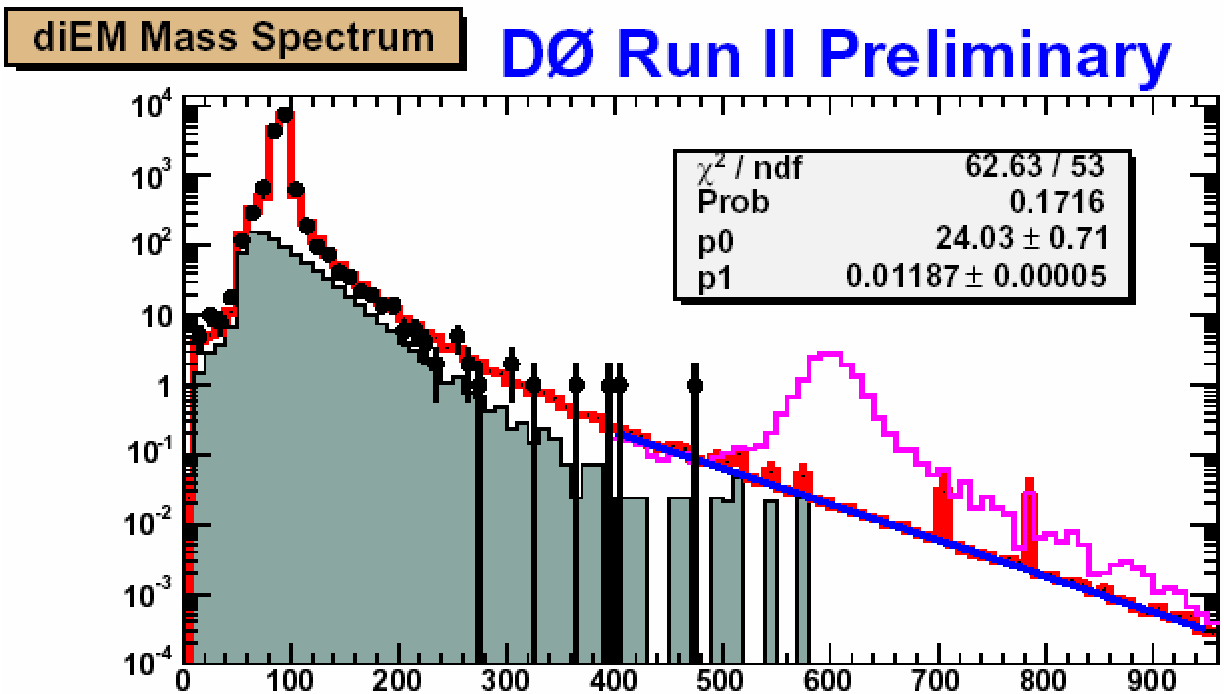
Diphoton Mass = 405 GeV

Photon Et = 172, 175 GeV

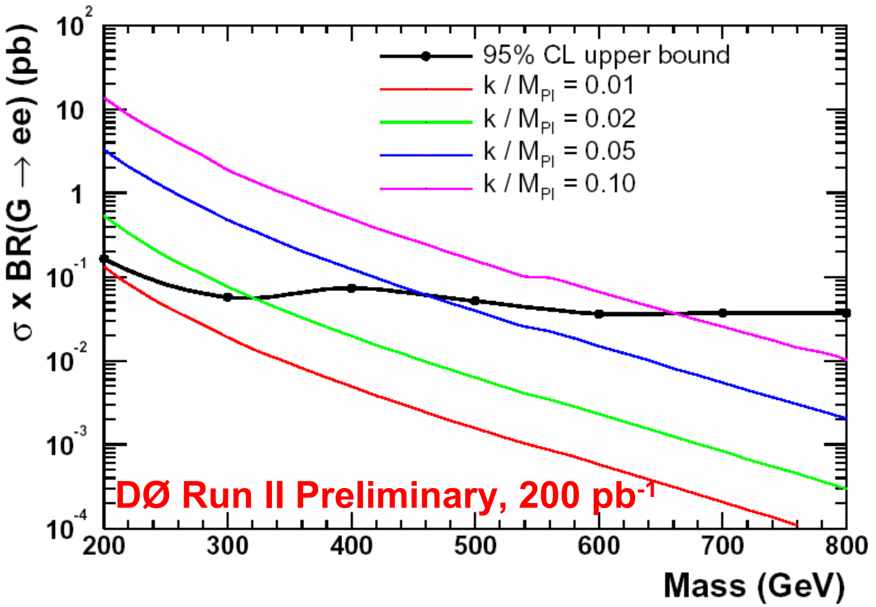


DØ Search for RS Gravitons

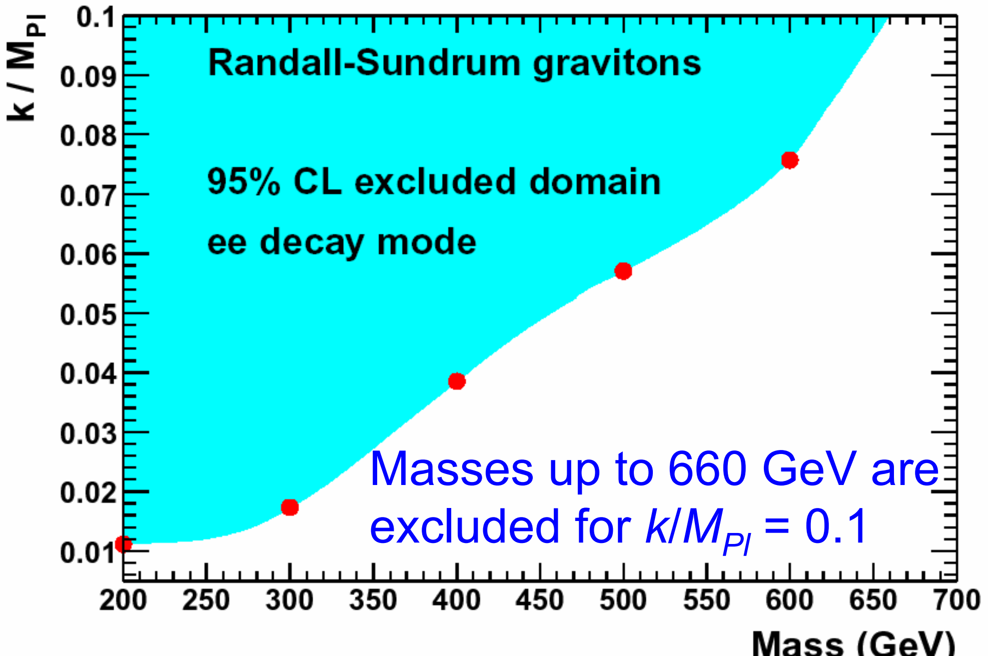
- DØ has just completed similar analysis and produced first results
- Analysis based on 200 pb^{-1} of e^+e^- data – the same data set as used for searches for TeV^{-1} ED
- Search window size has been optimized to yield maximum signal significance
- Analysis technique is similar; acceptance is somewhat higher



DØ Limits in the Dielectron Channel



Assume fixed *K*-factor of 1.3 for the signal



Cross section scales as $(k/M_{Pl})^2$

Masses up to 660 GeV are excluded for k/M_{Pl} = 0.1

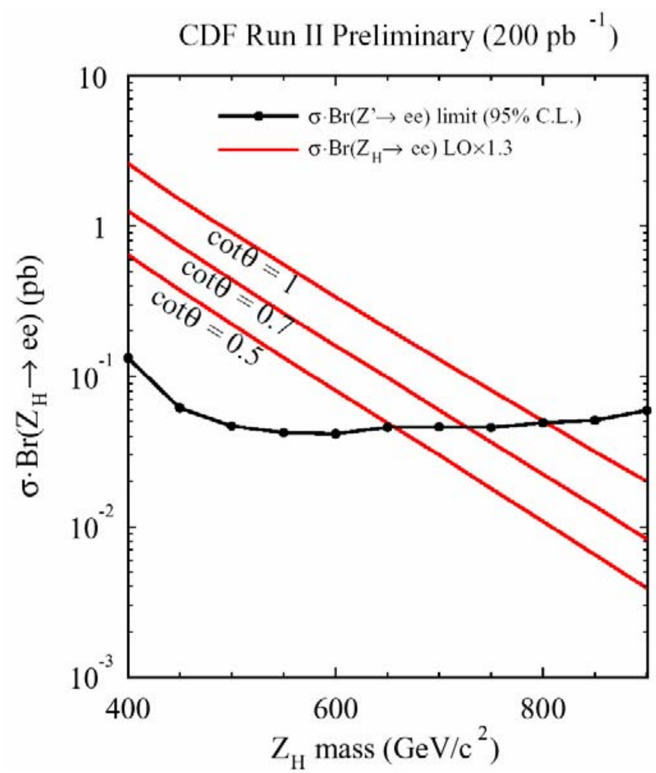
DØ Run II Preliminary, 200 pb^{-1}

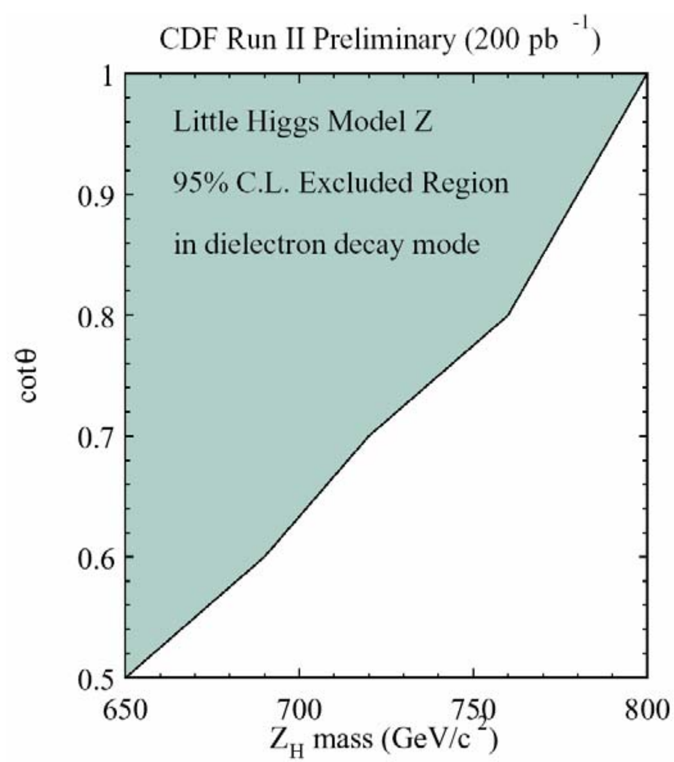
Almost No Extra Dimensions

- Novel idea: build a multidimensional theory that is reduced to a four-dimensional theory at low energies [Arkani-Hamed, Cohen, Georgi, Phys. Lett. **B513**, 232 (1991)]
- An alternative EWSB mechanism, the so-called Little Higgs (a pseudo-goldstone boson, responsible for the EWSB) [Arkani-Hamed, Cohen, Katz, Nelson, JHEP **0207**, 034 (2002)]
- Limited low-energy phenomenology: one or more additional vector bosons; a charge +2/3 vector-like quark (decaying into V/h+t), necessary to cancel quadratic divergencies), possible additional scalars (sometimes even stable!), all in a TeV range
- Unfortunately, the Tevatron reach is not very large; LHC would be the machine to probe this model
- However: started looking for this types models as a part of more generic search for Z′

CDF Limit On Z_H

- Littlest Higgs model: an additional gauge boson Z_H with the SU(2) coupling parameter $\cot\theta$ [Han, Logan, McElrath, Wang, PRD **67**, 095004 (2003)]
- Search done in the e^+e^-, $\mu^+\mu^-$ (200 pb^{-1}) mode; best sensitivity is in dielectrons
- Straight extension of the RS graviton/Z′ analyses
- Limits are far from theoretically motivated masses, but a good start!





Masses up to 800 GeV are excluded for $\cot\theta = 1$

Conclusions

- Colliders offer ultimate probe of models with extra spatial dimensions
- Tevatron is the highest-energy machine today and has an excellent opportunity to find first signs of extra dimensions in space
- Accelerator performance is excellent and both CDF and DØ have a large number of new results in this area
- Sensitivities beyond existing limits have been achieved already:
  - Tightest limits on large ED to date
  - First limits on RS gravitons
  - First test of Little Higgs models
- Stay tuned for more exciting results to come with much larger data set – any day now could bring an exciting discovery!